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Vaal's Microplastic Burden: Uncovering the Fate of Microplastics in Emfuleni Municipality's Wastewater Treatment Systems, Gauteng, South Africa

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Abstract: Municipal wastewater treatment plants (WWTPs) in Gauteng, South Africa, are inadequately designed or optimized to effectively remove microplastics (MPs), resulting in approximately 80% of wastewater being discharged into aquatic ecosystems with insufficient treatment. This study evaluates the prevalence and abundance of MPs in municipal WWTPs and their subsequent introduction into receiving water bodies. Comprehensive sampling was conducted across three municipal WWTPs in the Emfuleni region of Gauteng province from October 2022 to July 2023. Initial MP identification and quantification were performed using light microscopy, while scanning electron microscope energy-dispersive X-ray spectroscopy (SEM/EDS) was employed to identify non-plastic particles and perform elemental analysis. The findings reveal significant seasonal variability in MP concentrations. The highest influent and effluent concentrations were recorded during October (spring), with influent values of 142 MPs/ℓ (WWTP 1), 124 MPs/ℓ (WWTP 2), and 132 MPs/ℓ (WWTP 3), and effluent concentrations of 120 MPs/ℓ (WWTP 1), 63 MPs/ℓ (WWTP 2), and 89 MPs/ℓ (WWTP 3). Conversely, the lowest MP concentrations were observed during April (autumn), with influent concentrations of 114 MPs/ℓ (WWTP 1), 141 MPs/ℓ (WWTP 2), and 78 MPs/ℓ (WWTP 3), and effluent concentrations of 99 MPs/ℓ (WWTP 1), 53 MPs/ℓ (WWTP 2), and 86 MPs/ℓ (WWTP 3). Fibers and filaments constituted the dominant MP morphology, primarily derived from polyester, nylon, and acrylic synthetic textiles. Dark-colored MPs, especially black, blue, and red particles, were predominant in the wastewater samples. This study underscores the critical role of WWTPs as conduits for MP contaminants into the environment and highlights the urgent need to develop and implement improved MP removal technologies in wastewater treatment systems. MP production is estimated to account for approximately 15–20% of total global plastic production, corresponding to an annual generation of approximately 52.5–80 million metric tons of MP. By addressing MP pollution, this research directly contributes to sustainability by promoting the protection of freshwater ecosystems, reducing anthropogenic pressures on aquatic biodiversity, and supporting the principles of sustainable development. The findings align with global and regional goals to enhance water quality management and promote sustainable urbanization practices in line with the United Nations Sustainable Development Goals (SDGs).

Keywords: wastewater; microplastics; synthetic textiles; water contamination; particle analysis

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1. Introduction

The contamination of marine ecosystems by plastics, alongside the widespread dispersal of micro- and nanoplastics in aquatic environments and sediments, has emerged as a critical global challenge [1]. The United Nations acknowledges this growing concern, emphasizing its strong connection to Sustainable Development Goal (SDG) 14, which aims to combat marine plastic pollution globally [1]. Since water quality plays a significant role in achieving water security, and represents a fundamental aspect of water management [2,3], anthropogenic significantly increase both the demand for and impact on water resources. In particular, the use of rivers for waste disposal exacerbates these pressures, affecting the quality and quantity of both groundwater and surface water. Consequently, these challenges ultimately influence the overall availability of water resources [2,4]. Insufficient financial resources are frequently cited as a major factor contributing to the observed inequality in water and sanitation in many countries; it also involves shortcomings in water resource management and governance [5]. In addition, inadequate development and implementation of policies and procedures related to water and sanitation have contributed to a lack of clarity in the government's efforts to deliver satisfactory services [5]. The deterioration of water resource quantity and quality, particularly in South African rivers has a detrimental impact on socio-economic advancement since it renders such water unfit for critical activities such as domestic and industrial use. Since surface water is most readily available for domestic use, it is more vulnerable to contamination from a variety of sources [6,7]. The quality of effluent from municipal wastewater treatment facilities is critical in selecting appropriate treatment techniques and monitoring its effects on the ecosystems of receiving water bodies. By examining influent wastewater and treated effluent data, the appropriateness of recovered water sources for water reuse may be determined [7]. One of the major contributors to contamination of water resources, in particular surface water resources, is the deterioration of municipal wastewater treatment systems and infrastructure. Municipal WWTPs are not currently adequately designed or optimised for the effective removal of MPs, and approximately 80% of wastewater globally flows back either untreated or partially treated into the aquatic environment, posing threats to downstream ecosystems as well as communities that rely on the river for drinking water [8].

In South Africa, the contamination of industrial wastewater is a significant issue. This rapidly developing nation faces a challenge owing to its limited freshwater resources and is now classified as water stressed. With only slightly more than 1200 m^3/person/year of fresh water available for its population of approximately 58.89 million people [7]. The effluents resulting from both industrial and residential activities stand as the second most common source of chemical and microbiological contamination in the country's water sources [7]. According to [7,9] previous studies have indicated that most WWTPs in South Africa seldomly treat their wastewater to acceptable levels. Others participate in direct discharge of industrial contaminating recipient surface water sources. Some WWTPs lack the capacity to remove large volumes of non-biodegradable debris (such as plastics), micro- and nanomaterials and heavy metals, which are then dumped into surface water sources [7,9].

Effluents generated by both industrial and domestic activities in South Africa's WWTPs are the second-most prominent sources of water pollution. They currently serve as significant contributors to the chemical and microbial contamination of the country's water sources [10]. Compared to marine ecosystems, MP contamination in freshwater systems in South Africa is a new environmental concern, and research on the topic is still in its early stages. The majority of previous research has concentrated on detecting and measuring MPs in large river systems, such the Vaal River, which has shown widespread contamination from industrial processes, wastewater discharge, and urban runoff. MP abundances ranged from 0.13 to 2.5 particles/m^3, for example, according to a research conducted on the Vaal River, with fibers and fragments being the most common morphologies [11]. In addition, knowledge gaps still exist in understanding the transport, fate and behaviour of MPs, particularly in WWTP's [12]. Comprehensive systematic research has not yet been carried out to establish a direct relationship and correlation between MPs, non-biodegradable waste and heavy metal pollution and the geographic proximity of industries within surrounding catchment areas [13]. Previous studies have shown that the quantities of MPs in effluent correspond with the operating load of WWTPs, with much greater MP concentrations reported in WWTPs that are overloaded [14,15]. Shorter hydraulic retention time triggered by overloaded operation translates into higher wastewater flow rates. Research findings suggest that, even with the implementation of contemporary technologies, WWTPs persist as a prospective pathway for the environmental release of MPs via the substantial daily discharge of effluent [14]. The limited knowledge of MP pollution in rivers and WWTPs is a central motivation for this study. As reported by [6], South Africa has a total of 824 WWTPs across 152 municipalities, with a collective design capacity of 6.5 billion litres. The present study is centred on the prevalence and abundance of MPs in WWTPs and their corresponding receiving waters, with the objective of acquiring in-depth insights into the abundance and transfer of MP from effluent to receiving aquatic environments. This study aims to bridge the knowledge gap and, concurrently, identify effective strategies for mitigating and reducing the influx of MPs into WWTPs and aquatic ecosystems. Consequently, this research is dedicated to exploring the presence, distribution and abundance of MPs. The overall objective is to enhance our understanding of the role played by WWTPs as transport vectors of these contaminants. While the realisation of MP remediation may be time-consuming, prevention is an immediate possibility. For preventive measures to be effective, it is crucial to understand the escape routes of MPs, especially those within existing wastewater management systems.

2. Materials and Methods

2.1. Study Location and Description

Despite being the smallest of South Africa's nine provinces and measuring just 18,178 km^2, Gauteng, (Figure 1) is widely acknowledged as South Africa's economic powerhouse. It has the highest population density and the fastest population growth rate among all the provinces in South Africa, Gauteng has a rich biodiversity since it is situated within both the grassland and savanna biomes [16]. Gauteng is positioned on the continental divide, from where various rivers flow either into the Indian Ocean or the Atlantic Ocean. The province is located in the headwaters of several important river systems within an urban environment. Notably, the Blesbokspruit, Klip River and Natal Spruit are integral to the Vaal River primary catchment. Additionally, the Apies, Hennops, Pienaars and Jukskei Rivers contribute to the Crocodile River West catchment, while the headwaters of the Olifants River primary catchment are also located in Gauteng [17].

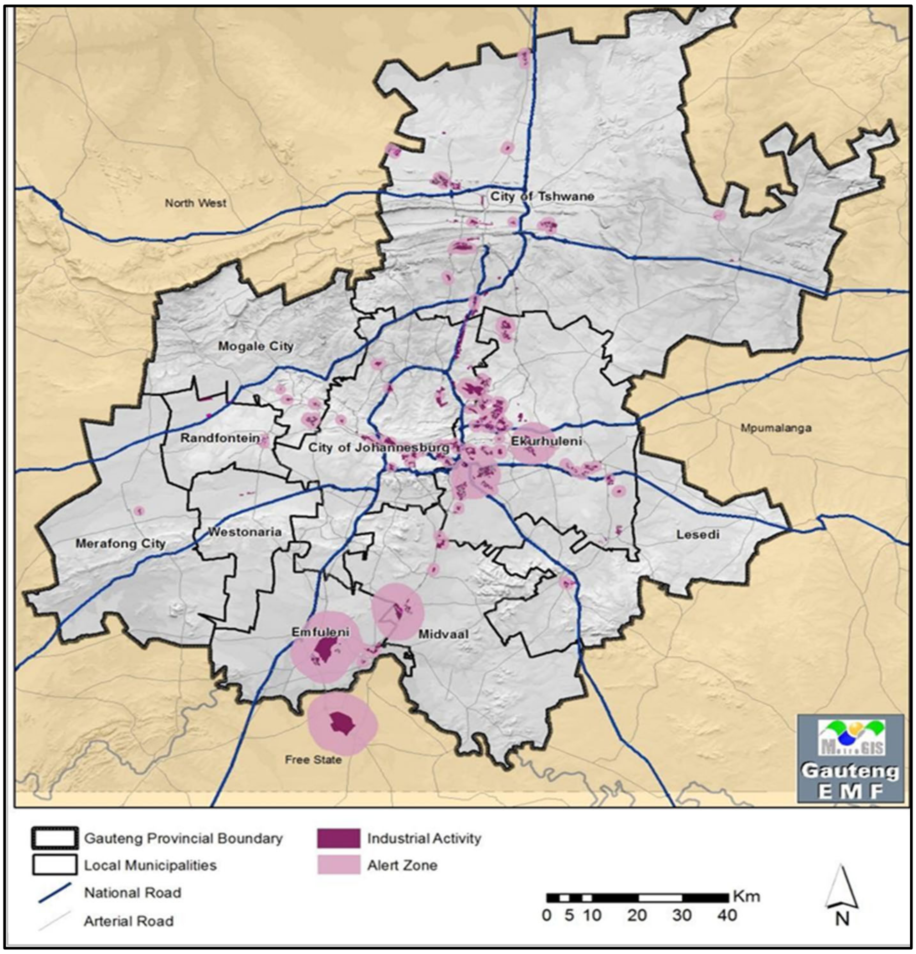

Figure 1. Map of Gauteng, including the local municipalities (Source: www.municipality.gov.za. Accessed: 28 December 2024).

2.2. Site Selection

Within Gauteng, the Sedibeng District Municipality is the sole region situated along both the Vaal Dam and Vaal River banks, historically referred to as the Vaal Triangle. Emfuleni Local Municipality is positioned in the westernmost part of the Sedibeng District Municipality, encompasses an area spanning 987.45 km^2 [18]. the Leeuwkuil, Rietspruit and Sebokeng WWTPs are located in the Emfuleni Local Municipality. The Leeuwkuil WWTP (referred to as WWTP 1 in this study) is situated in the jurisdiction of Vereeniging, falling in Emfuleni Local Municipality. Established in 1958 with a proposed handling capacity of a population equivalent of 83,050, the Leeuwkuil WWTP holds a capacity of 36,000 m^3/d. It comprises an activated sludge plant with a capacity of 20,000 m^3/d and a trickling filter system with a capacity of 16,000 cubic metres per day [13]. Owing to rapid industrial development pressures and population growth in the vicinity, the existing Leeuwkuil WWTP now receives an average daily waste flow of about 42,000 m^3/d, exceeding the plant's design capacity by 116% [13]. A study revealed that by the year 2016, several bio-filters had become inoperative owing to ageing infrastructure and inadequate maintenance. For instance, the bio-filter facility, designed for a capacity of 16,000 m^3/d was receiving an average influent flow of approximately 2000 m^3/d, with the surplus hydraulic capacity of 40,000 m^3/d being managed by the activated sludge plant, originally designed for a capacity of 20,000 m^3/d [13]).

The Rietspruit WWTP (referred to as WWTP 2 in this study) is situated to the west of Bophelong, adjacent to a decommissioned airfield. This facility operates with two distinct process streams: a BNR process with a design capacity of approximately 20 Mℓ/day, and a bio-filter process with a design capacity of around 16 Mℓ/day. Currently, the average chemical oxygen demand (COD) loadings range from 120 to 333 mg/ℓ. The bio-filters can handle a raw sewage COD of 600 mg/ℓ or 13 tonnes of COD after 35% removal in the primary settlement tanks [19]. To manage the flow, the bio-filter input must be limited to 32 Mℓ/day, while any excess flows are directed to the BNR stream. Currently, the flow directed to the bio-filters is restricted to around 20 Mℓ/day. With the expansion of irrigation beyond the Pilot Project, the bio-filter load can be increased to 32 Mℓ/day, thus freeing up 14 Mℓ of BNR capacity for new developments. Initially, about 10 Mℓ/day will be allocated to the Pilot Project, while 10 Mℓ/day will be discharged into the Vaal River, as it is currently [19].

The Sebokeng WWTP (referred to as WWTP 3 in this study) is situated in the area west of Sebokeng, between the N1 concrete road and the Golden Highway. It receives wastewater from the City of Johannesburg to the north. The plant comprises two BNR units with a total capacity of 50 Mℓ/day, with a third under construction and a fourth planned. The present average COD loading on the plant is ± 200 mg/ℓ.

2.3. Study Design and Sample Collection

Bulk water sampling was performed using a metal bucket affixed to a chain, which was systematically lowered into the influent and effluent streams of WWTP 1, 2, and 3. Sampling was conducted seasonally from October 2022 to July 2023, with a single collection event per season (Spring: October 2022, Summer: January 2023, Autumn: April 2023, Winter: July 2023). This was done to assess potential seasonal variations in the abundance and composition of microplastics (MPs).

At each sampling location, two water samples (influent and effluent) were collected per season, with each sample comprising 1 L. Prior to storage, samples were filtered through a 0.5 mm metal sieve to remove larger particulates. The processed samples were then transferred into prewashed 1.5-L polyethylene containers, stored in a cold box at 3 °C, and transported to the laboratory for further analysis within eight weeks of collection to preserve sample integrity

2.4. Sample Digestion, Filtration and Microplastic Extraction

Wastewater samples were collected and deposited into glass beakers sealed with aluminium foil [20]. Since sewage water is likely to contain pathogens, the samples were transferred into glass Erlenmeyer flasks and then treated with 30% hydrogen peroxide for digestion of labile organics and were heated in a water bath to 75 °C for 30 min to expedite the reaction. A magnetic stirrer was used on the spiked samples for 10 min. Digestion was allowed to continue at room temperature for three days. After the digestion period, samples were treated with UV light for 30 min to verify that they were sufficiently sterile to be removed from the biological safety cabinet room for filtration under vacuum through Whatman 1.2-µm glass fibre filters (47 mm diameter). Samples were then filtered to decrease the potential loss from on-site filtration of smaller MPs. For maximum drying, MP samples (free of organic material) were placed in a Memmert vacuum oven-PM400 (manufactured by Memmert GmbH + Co. KG, In Schwabach, Germany) at 90 °C for 72 h.

2.5. Identification of Microplastics

2.5.1. Visual Identification of Microplastics

Light microscopy was used in the initial phase of sample identification and quantification for this study. This was a crucial step, as the subsequent characterisation process depended on the capability to first recognise MPs and then manually relocate them for instrumental analysis. MPs were visually identified based on their shape and colour using a Carl Zeiss Stemi DV4 dissection microscope (manufactured by Carl Zeiss AG, in

Oberkochen, Baden-Württemberg, Germany). with magnification ranging between 10× and 32×. Identification was based on a modified version of the step-by-step guide that was established by [21,22].

MPs were categorised into primary and secondary groups. In the primary category were pellets commonly found in personal care items such as toothpaste and exfoliant face washes; these resembled a round or cylindrical shape. Secondary MPs were characterised as fragments or films that appeared to be irregular in shape, and which could have resulted from the fragmentation of larger plastic particles. Fibres composed of different lengths and widths were also classified as secondary MPs that could have resulted from fishing lines and rope fragments, or the shedding of threads during regular clothing use or laundry cycles.

2.5.2. Morphological Characterisation Using Scanning Electron Microscope

SEM-EDS was utilised to screen the samples for non-plastic particles, such as glass pellets, fragments and metals that potentially imitate plastic particles. SEM/EDS analysis comprised a pixel size of 0.06 µm, an acceleration voltage of 15 kV, and a magnification range of 40× to 6400×. To prevent interference with the peaks of other substances, MP particles were transferred from a Petri dish onto the specimen stage of an SEM coated with a 50 nm layer of carbon. The specimen chamber of the SEM was closed, and pressure equalisation was achieved by activating the vacuum pumps for 5–10 s at 10^{-3} Torr. The SEM, along with its energy-dispersive X-ray system, was adjusted to a voltage of 15 kV. To generate primary electrons, the magnification was adjusted within the range of 40× to 6400×, and the sample was scanned using a beam with high-energy settings and a map resolution of 512 × 384. The SEM, in conjunction with energy-dispersive X-ray, operated in backscattered imaging mode. This mode allowed the primary electrons to interact with the samples, generating secondary electrons, backscattered electrons and X-rays. Electron and X-ray detectors within the scanning electron microscope were utilised to capture signals, producing images with a pixel size of 0.06 µm and a maximum magnification of 5200×, which were displayed on the computer monitor.

2.5.3. Elemental Particle Analysis Using a Scanning Electron Microscope

SEM/EDS analysis was used to conduct elemental analysis, with the objective of identifying elemental components, particularly heavy metals, often linked to the presence of MPs in water. The detection of elements such as aluminium, chloride, iron, manganese, silicon, zinc and other heavy metals on MPs, implies the capacity of MPs to disseminate pollutants. The detection of elements was enabled through the interaction of primary electrons with the samples, generating secondary electrons, scattered electrons and X-rays. Subsequently, the X-ray detector was utilised to identify the mentioned elements [23].

2.5.4. Vibrational Spectroscopy by Fourier-Transform Infrared (FTIR)

Polymer identification involved molecular mapping using reflectance FTIR performed using a Perkin-Elmer spotlight imaging FTIR microscope model in the 600 to 4000 cm^{-1} mid-IR region. Spectral results were derived using the focal plane array method, relying on reflectance in imaging mode, incorporating two co-added scans per pixel, an aperture size of 25 m^2, and maintaining a spectral resolution of 16 cm^{-1}. This method of acquiring spectra facilitated the rapid identification of polymers. A specialised polymer library containing spectra commonly linked with MPs was utilised to confirm the comparison of polyethylene spectra. FTIR peaks specific to polymers were utilised to cross-reference the functional groups identified within absorption regions.

2.6. Quality Assurance and Quantity Control

Ensuring data accuracy during the sampling process necessitated strict adherence to quality assurance (QA) and quality control (QC) protocols. Laboratory personnel wore 100% cotton lab coats and latex gloves throughout the process to minimize contamination. To prevent cross-contamination between consecutive washes, the vacuum funnel and filter membrane were rinsed with 500 mL of Milli-Q water prior to reassembly for subsequent use. Similarly, the ceramic roaster and soup bowl were thoroughly cleaned using 500 mL of Milli-Q water and placed on sterile aluminium foil to maintain cleanliness. To mitigate potential contamination from airborne microplastics (MPs), all collected samples were securely stored in sterilized Petri dishes, and glass flasks were covered with aluminum foil. Additionally, blank tests were performed to account for environmental contamination due to the ubiquitous presence of MPs in the atmosphere. These blank tests involved processing sterilized glass flasks and Petri dishes without adding wastewater samples, allowing for the identification of any MPs or contaminants inadvertently introduced during sample handling and storage This approach enabled the differentiation between MPs originating from collected wastewater samples and those potentially introduced from external sources, ensuring that the analytical results accurately reflected the contamination levels in the wastewater. To ensure that the hydrogen peroxide digestion process did not compromise MP recovery in our study, control experiments were conducted by subjecting known MP particles to identical digestion conditions. Subsequent analyses revealed no significant changes in polymer morphology or structural integrity, confirming that the applied hydrogen peroxide treatment did not adversely affect MP recovery. In addition, all sampling procedures were performed in triplicate to ensure reproducibility. The collected samples underwent both qualitative and quantitative microscopic analysis, as well as structural characterization. Quantitative data are reported as the mean of three replicates, with statistically significant variations observed. However, no qualitative differences were detected in microscopic and structural characteristics across the replicates.

3. Results

3.1. Microplastic Abundance

WWTP 1 was observed to have the highest concentration of MPs throughout the study. This is largely due to the malfunctioning of the wastewater infrastructure at this plant. A previous study that investigated the state of South Africa's municipal WWTPs, revealed that WWTP 1 was producing discharge effluent that was indistinguishable from the untreated sewage entering the facility [24]. In the present study, it was noted that the concentrations of MPs fluctuated seasonally across the sampling points. Samples were collected in October 2022 (Spring), January 2023 (summer), April 2023 (autumn) and July 2023 (winter).

During the October sampling period (spring season), the highest MP concentrations were observed, as depicted in Figure 2. This peak can be attributed to elevated surface runoff associated with spring rainfall. The runoff facilitates the transport of MPs from industrial, agricultural, and urban areas into the wastewater system. Additionally, warmer spring temperatures may accelerate the degradation and fragmentation of larger plastic debris, thereby increasing the availability of MPs for transport into wastewater systems. The influent MP concentrations were 142 MPs/ℓ for WWTP 1, 124 MPs/ℓ for WWTP 2 and 132 MPs/ℓ for WWTP 3. When comparing seasonal effluent MP concentrations (Figure 2) MP concentrations were observed to be the highest during the October sampling (spring season), where the MP count showed MP concentrations were 120 MPs/ℓ (WWTP 1), 63 MPs/ℓ (WWTP 2) and 89 MPs/ℓ (WWTP 3). These MP concentrations were observed to be far lower than those documented in other literature which utilised similar materials and methods and comparable size ranges [25]. The lowest concentration of MP counts was observed during the April sampling period (Autumn season) as seen in Figure 2. The influent MP concentrations were 114 MPs/ℓ (WWTP 1), 141 MPs/ℓ (WWTP 2) and 78 MPs/ℓ (WWTP 3). In addition, effluent MP concentrations were 99 MPs/ℓ (WWTP 1), 53 MPs/ℓ (WWTP 2) and 86 MPs/ℓ (WWTP 3). Emfuleni Municipality's WWTPs study on MP seasonal variations revealed that the lowest concentrations were noted in autumn, whereas the highest concentrations were noted in spring. Findings from the July sampling period (winter) further illustrated high influent MP concentrations and low effluent MP concentrations, resembling the study conducted by [26].

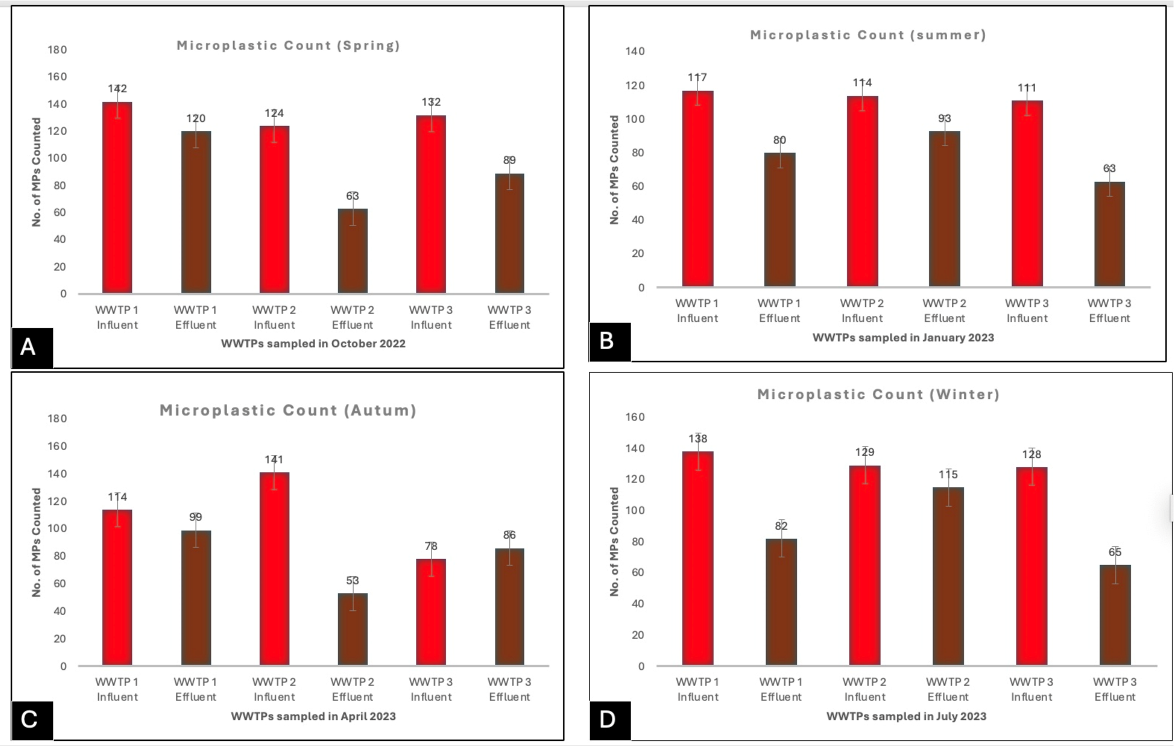

Figure 2. Microplastic counts of influent and effluent wastewater sampled at Emfuleni Municipality in Gauteng South Africa. (**A**): Microplastic counts of influent and effluent wastewater sampled in October 2022 (Spring season), (**B**): Microplastic counts of influent and effluent wastewater sampled in January 2023 (Summer season), (**C**): Microplastic counts of influent and effluent wastewater sampled in April 2023 (Autum season) and (**D**): Microplastic counts of influent and effluent wastewater sampled in July 2023 (Winter season).

3.2. Microplastic Particle Analysis

The relative abundances of various shapes of MPs observed in Emfuleni Municipality's WWTPs are presented in Figure 3. In the influent samples, findings revealed that fibres and filaments constituted the predominant portion of the observed MPs in the wastewater, comprising an average proportion of 72%. This aligns with previous studies by [27,28] that also noted the prevalence of fibres and filaments in WWTPs. The significant presence of these fibres and filaments in this study could be attributed to the discharge of synthetic fibres and filaments from household washing machines [27,29]. In effluent samples (Figure 3), it was found that fibres and filaments also formed the major portion (73%) of the observed MPs in the wastewater. Seasonal variations were noted to have no impact on the abundance of fibres and filaments. In effluent samples (Figure 3), it was found that fibres and filaments also formed the major portion (73%) of the observed MPs in the wastewater. Seasonal variations were noted to have no impact on the abundance of fibres and filaments.

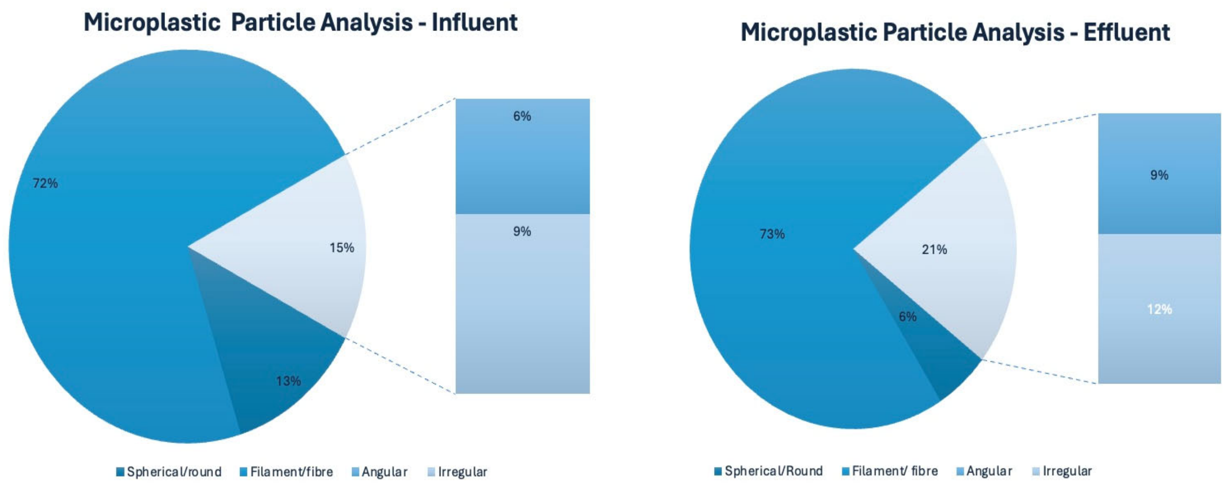

Figure 3. Microplastic Particle Analysis of influent and effluent wastewater sampled at Emfuleni Municipality in Gauteng South Africa during the period October 2022 to July 2023.

3.3. Colour Distribution of Microplastics

Identified MPs, as classified by [30], can be categorised into dark shades (such as black and blue) medium tones (such as light blue, brown and red) and light tones (such as yellow, white and transparent) [30]. In this study, abundance in dark hues (black and blue) constituted the majority, comprising 88.54% in the influent and 85.38% in the effluent. Nevertheless, MP in lighter shades like white and green were also commonly observed in both influent and effluent samples (Figure 4). The elevated presence of MPs in dark tones (black, blue and red) can be attributed to the prevalent utilisation of plastics infused with dyes or pigments to produce various items such as textiles and other food and packaging materials.

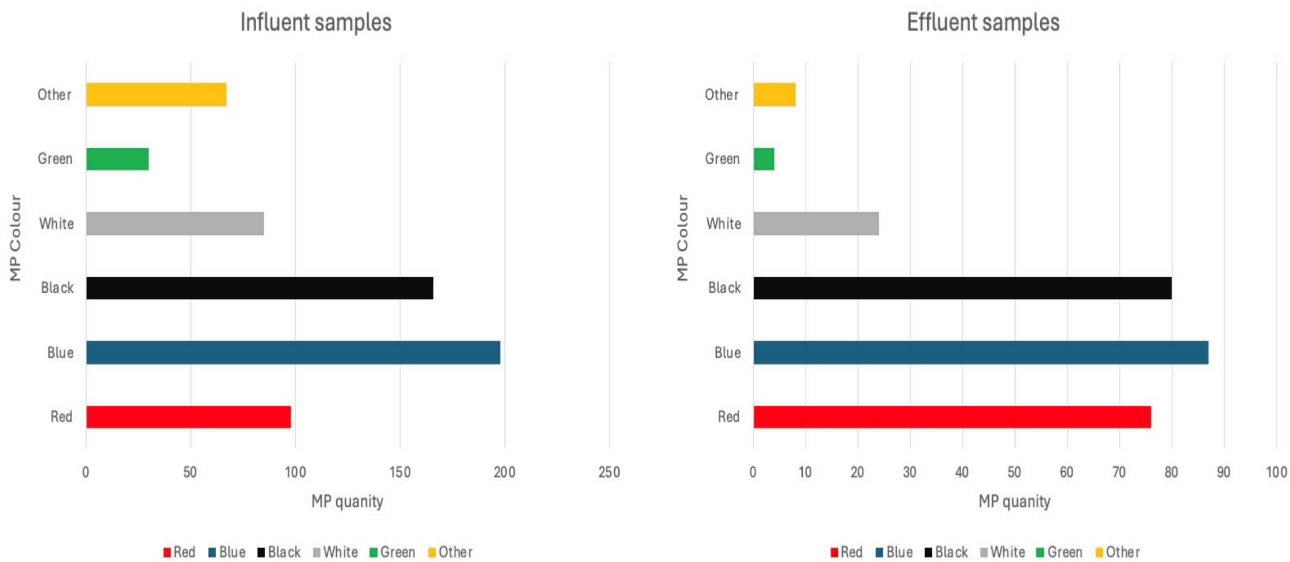

Figure 4. Colours of MPs observed in effluent wastewater samples collected at Emfuleni Municipality between October 2022 and July 2023.

3.4. SEM Microplastics Analysis

The SEM-EDS analysis findings of the current research align with the visual examination of MP of this manuscript, indicating that filaments and fibres constitute most of the MPs at WWTPs 1–3. These filaments and fibres accounted for 81% and 78% of MPs in influent and effluent, respectively, with diameters ranging from 0.05 mm (50 μm) to

0.025 mm (25 µm). Filamentous/fibrous MP particles were consistently present in WWTPs 1–3 (Figure 5) across all seasons.

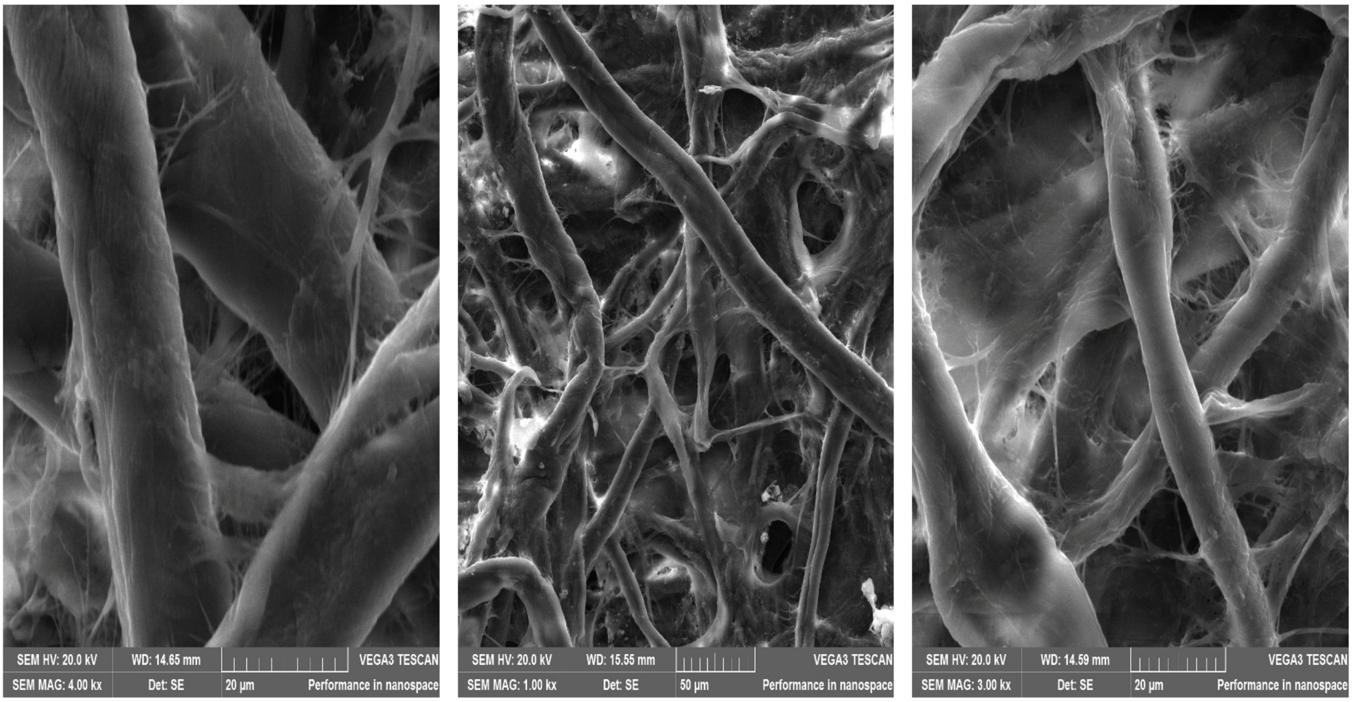

Figure 5. SEM image of an MP particle from a wastewater sample from WWTP1–3 at Emfuleni Municipality's influent and effluent flow. The image shows the surface morphology of a filamentous MPs.

3.5. SEM-EDS Analysis

Based on the results of the chemical composition shown in Figure 6 (WWTP 1), the elemental composition closely resembles the typical makeup of PET, which consists of 54.2% carbon and 42.8% oxygen. PET is widely used in the manufacturing of food packaging, textiles and plastic bottles for beverages [31].

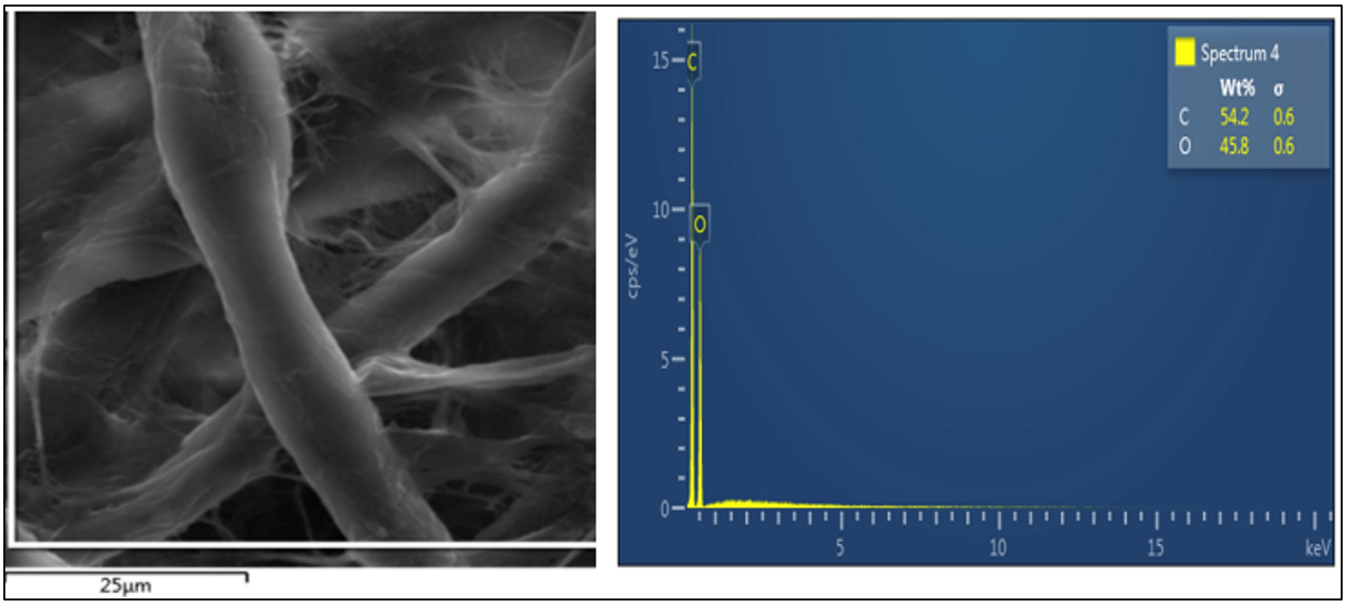

Figure 6. SEM-EDS image of an MP particle from a wastewater sample from WWTP1 at Emfuleni Municipality's influent flow.

Figure 7 (WWTP 2 (A) resembles the elemental composition of PVC, which includes carbon, oxygen and small percentages of silicon, iron, zinc and calcium. PVC has extensive applications including pipes. While Figure 7 (WWTP 3 (B) resembled the elemental composition of PET.

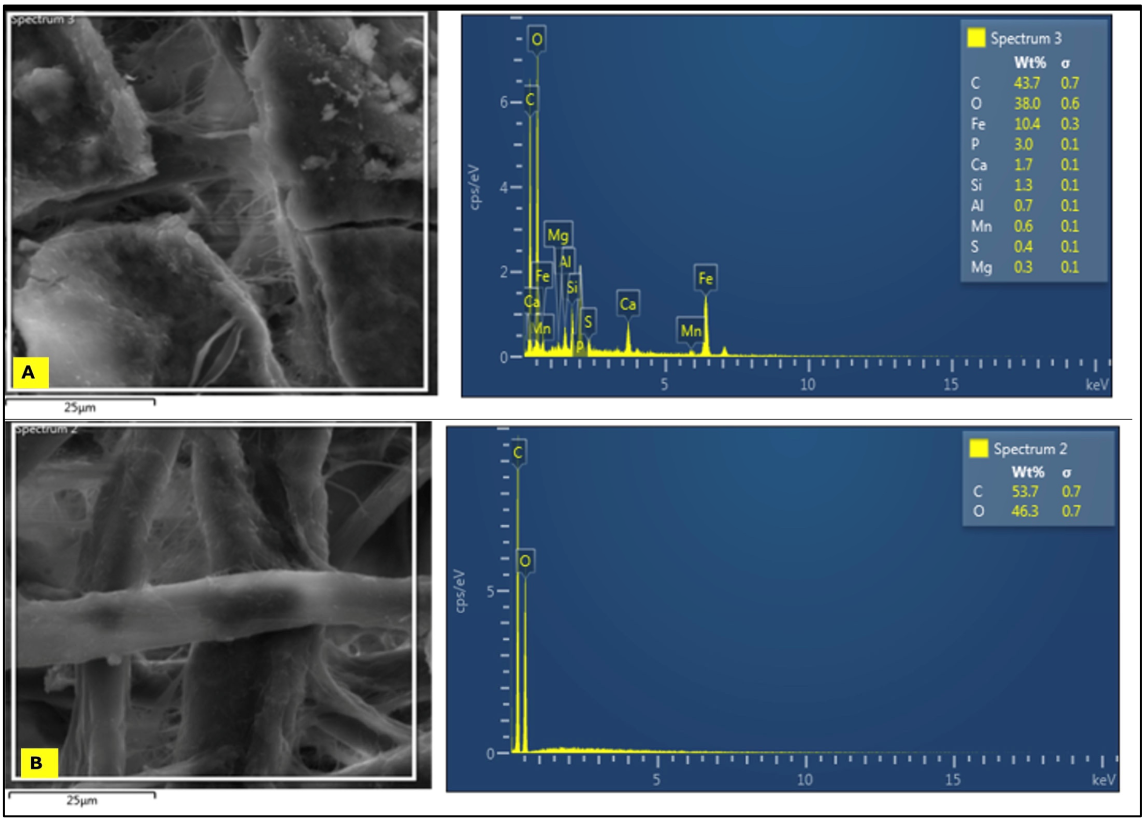

Figure 7. SEM-EDS image of an MP particle from a wastewater sample from WWTP2 (**A**) and WWTP3 (**B**) at Emfuleni Municipality, Gauteng, South Africa.

3.6. FTIR Analysis

According to the findings of this study, the predominant MP polymers identified across WWTPs 1 to 3 during the sampling in October 2022 to July 2023 were PE's (Figure 8), (further categorised into high-density polyethylene (HDPE) and low-density polyethylene (LDPE). HDPE and LDPE are the most prevalent forms of polyethylene. They are synthesised either as high-density or low-density PE through the process of addition polymerization of ethylene with organometallic catalysts. HDPE contains polymer chains ranging from 500,000 to 1,000,000 carbon units in length without any branching and exhibits a higher proportion of crystalline regions [32]. Consequently, HDPE tends to be tougher and opaquer compared to LDPE and is used in the manufacturing of various plastic items such as packaging, food containers and drinking bottles. In contrast, LDPE is characterised by a significant presence of short- and long-chain branching, suggesting a looser packing of chains in its crystal structure [33]. The presence of PE can result from a variety of sources, including stormwater runoff, industrial discharges, household and municipal garbage, and, to a lesser extent, PE-based microbeads or fibers from cleaning goods and textiles. During this study, when analysing seasonal variations, the autumn and winter sampling periods exhibited an abundance of PE polymer composition. These seasonal variations could have been attributed to the increase of domestic sewage from washing machines entering WWTPs during winter, as there is a tendency to wear more fibre-rich clothing during winter. The FTIR functional groups associated with polymers appear to remain consistent across seasons. Compounds within the 1500–4000 cm^{-1} range were identified based on their functional groups.

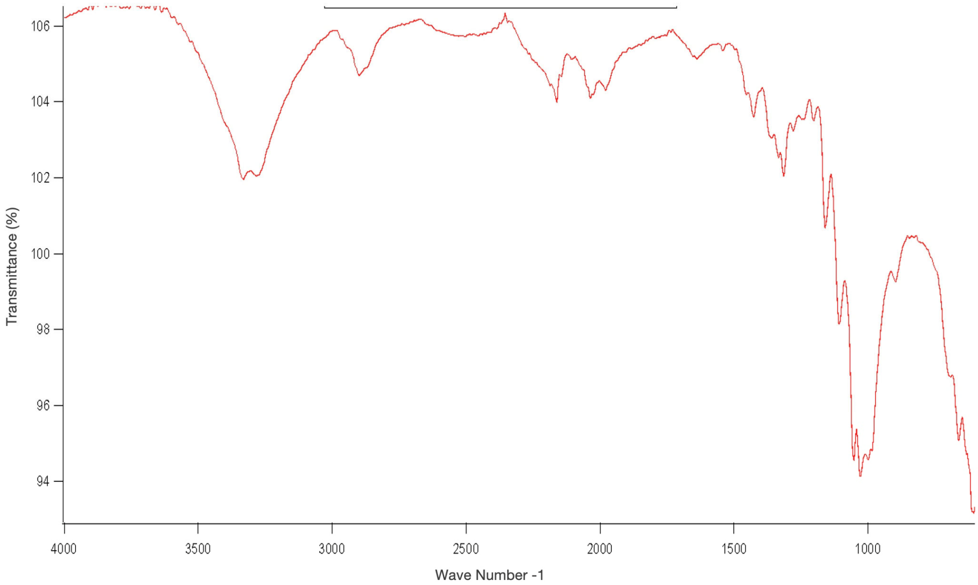

Figure 8. FTIR analysis indication of the presence of PE in influent at WWTP 2 in Emfuleni Municipality, Gauteng, South Africa.

4. Discussion

During MP abundance analysis of wastewater samples obtained at WWTPs in Emfuleni Municipality, it was noted that there were variations in MP concentrations between different treatment plants (WWTPs 1, 2 and 3, respectively). This variation in MP concentrations was influenced by a variety of factors which include but are not limited to: (1) the source of wastewater, (2) the presence of combined sewer systems in and around Emfuleni, and (3) the population served and the surrounding land use [34]. There was a substantial portion of MPs found in wastewater that originated from household laundry discharges, which directly influenced the concentration of MP in the wastewater. This was similar to studies by Mason et al. [35] who conducted a comprehensive study on 17 wastewater treatment facilities in the United States, encompassing varying population densities, size of geographical locations and varying filtration technologies.

Emfuleni Municipality's WWTPs study on MP seasonal variations revealed that the lowest concentrations were noted in autumn, whereas the highest concentrations were noted in spring. Findings from the July sampling period (winter) further illustrated high influent MP concentrations and low effluent MP concentrations, resembling the study conducted by [29]. Emfuleni Municipality's findings were in contrast with the findings of a study conducted by [36] in a WWTP in Gumi, South Korea [36] found that in influent, the lowest concentration of MPS was found in April (northern hemisphere spring) and the highest MP concentration was found in July (northern hemisphere summer). Ref. [36] discovered that in effluent samples, there were no variations in MP concentrations across the four seasons. WWTPs in developed nations, such as South Korea and the United States, typically employ innovative technologies, including ozone treatment, advanced oxidation processes (AOPs), and membrane bioreactors (MBRs). These innovative systems, coupled with substantial investments in modern technologies, regular maintenance, and a strong emphasis on environmental protection, enable WWTPs in these regions to achieve high operational efficiency and effective removal of MPs.

In contrast, South Africa is still grappling with the emerging issue of MP contamination in wastewater, with limited understanding of the efficacy of current WWTPs in removing

MPs. Despite the presence of comprehensive environmental regulations in South Africa, enforcement remains inconsistent. Legislative frameworks such as the Water Services Act (1997) and the National Water Act (1998) mandate appropriate wastewater management; however, compliance levels are relatively low. This is attributed to factors such as political interference in municipal decision-making and inadequate monitoring of effluent discharge from wastewater treatment plants (WWTPs). Furthermore, a significant number of WWTPs, including those within Emfuleni Municipality, operate beyond their design capacity. For instance, the Leeuwkuil WWTP currently processes 42,000 m^3/day, exceeding its intended capacity by 116%. The inability to expand infrastructure has led to increased sludge accumulation, resulting in elevated pollutant concentrations in effluent discharge. Additionally, reduced hydraulic retention time compromises the removal efficiency of MPs and other contaminants. South African WWTPs also lack advanced filtration technologies, such as MBRs and AOPs, which are widely implemented in developed countries to enhance treatment efficiency. This technological deficiency, coupled with financial constraints and weak policy enforcement, significantly limits the capacity of these facilities to effectively mitigate MP contamination. Findings of this study further revealed that fibres and filaments constituted the predominant portion of the observed MPs in the wastewater,. This aligns with previous studies by [27,28] that also noted the prevalence of fibres and filaments in WWTPs. In this study, abundance in dark hues (black and blue) constituted the majority, comprising 88.54% in the influent and 85.38% in the effluent. Nevertheless, MP in lighter shades like white and green were also commonly observed in both influent and effluent samples (Figure 4). These findings contradict the findings from an investigation by [37] which found that white and clear emerge as the predominant colours of MPs in wastewater, constituting 55.1% and 50.3% of the total MP count in the influent and effluent, respectively.

The SEM-EDS analysis findings of the current research align with the visual examination of MP of this manuscript, indicating that filaments and fibres constitute most of the MPs at WWTPs 1–3. The findings of this study align with earlier studies conducted by [38] that also observed high concentrations of fibres in influent and effluent samples. As previously discussed, these fibres originate from the degradation and subsequent release of synthetic fibres from textiles into domestic sewage systems [38–41].

The elemental analysis using EDS of the examined wastewater samples indicated the presence of prominent peaks for carbon and oxygen in all samples; this was in line with the study by [41] which found strong carbon and oxygen peaks in samples in sediment of freshwater urban rivers in Scotland (United Kingdom). Traces of other elements including aluminium, calcium, cadmium, cobalt, copper, iron, magnesium, nickel and zinc were detected at low levels, suggesting possible contamination of MPs by suspended solids in wastewater.

During this study, when analysing seasonal variations, the autumn and winter sampling periods exhibited an abundance of PE polymer composition. These seasonal variations could have been attributed to the increase of domestic sewage from washing machines entering WWTPs during winter, as there is a tendency to wear more fibre-rich clothing during winter. The FTIR functional groups associated with polymers appear to remain consistent across seasons. Compounds within the 1500–4000 cm^{-1} range were identified based on their functional groups. The findings of the current study align with the previous studies on the characterisation of MP particles using FTIR, which also includes a meta-analysis of 68 environmental MP studies which indicated that PE was the common polymer found in environmental samples [21]. Research carried out by [29,38] similarly identified PE as the most abundant MP in samples collected from WWTPs in Germany.

5. Conclusions

Emfuleni Municipality MP concentrations varied from 0 to 183 MPs/ℓ for influent while effluent concentrations ranged from 0 to 78 MPs/ℓ due poor working conditions of the Emfuleni WWTPs. In addition, Seasonal fluctuations were evident, with MP concentrations peaking during specific periods, such as October 2022. Similar patterns were observed in both municipalities, suggesting a degree of consistency in the dynamics of MP abundance in WWTPs. Further analysis revealed a positive correlation between the abundance of MPs and the population density and levels of industrialisation in adjacent catchment areas. Furthermore, findings of this study found that fibre and filament-shaped MPs were prevalent in both influent and effluent samples from all WWTPs. Spherical MPs showed a decrease from influent to effluent samples, while angular and irregular MPs remained relatively stable. Moreover, dark-coloured MPs—particularly black, blue and red—constituted most MPs in wastewater samples, followed by light-coloured MPs such as white, green and yellow. SEM-EDS analysis findings aligned with visual examinations, indicating that filaments and fibres predominantly comprised the MPs across WWTPs 1–3, with consistent presence across all seasons. Additionally, non-plastic cellulose-based fibres were identified. These findings are consistent with previous studies, which noted a higher concentration of fibres originating from textile degradation in both influent and effluent samples. These synthetic fibres and filaments mainly originated from polyester, nylon and acrylic, which constitute the primary materials used in synthetic textiles, accounting for 60% of the synthetic fibre market. synthetic textiles are identified as the largest contributors to MPs in WWTPs. Despite advancements in characterizing MPs in WWTPs, further research and targeted interventions are necessary to enhance MP removal efficiency. The adoption of MBRs, sand filtration, and electrocoagulation has shown promise in improving wastewater treatment, particularly for MP removal. However, the high investment and operational costs, skilled labor shortages, and energy constraints present significant challenges to immediate implementation in South Africa. A phased approach is recommended, starting with pilot MBR projects in high-priority municipal WWTPs, followed by gradual expansion through public-private partnerships and cost-effective alternatives in under -funded areas. Infrastructure maintenance remains a priority.

Establishing a dedicated wastewater infrastructure fund, conducting regular maintenance audits, can enhance system resilience. To address governance challenges, enhanced regulatory enforcement mechanisms should be established, including regular effluent monitoring, incentivized compliance programs for municipalities, and an independent oversight body to improve transparency in WWTP management. Additionally, capacity-building initiatives should focus on training wastewater personnel, creating employment opportunities for unemployed environmental graduates, and facilitating international knowledge exchange programs to build technical expertise. In addition, public engagement is critical in mitigating MP pollution at the source. National awareness campaigns should promote sustainable plastic consumption practices, building on South Africa's existing plastic bag levy model. Integrating zero-waste education into school curricula can foster long-term behavioral shifts. MP abundance in the environment can greatly be decreased by zero plastic waste initiatives, which are especially successful at reducing the production of plastic waste. In order to encourage businesses and consumers to adopt more sustainable practices, plastic levies have been implemented as a financial tool to support recycling initiatives and reduce plastic usage. A comprehensive and context-specific approach—combining incremental technological upgrades, strengthened regulatory enforcement, workforce development, public education, and infrastructure investments—is essential to effectively reduce MP contamination and improve wastewater management in South Africa.

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